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METEORITE CRATERS

B. A. Ivanov and A. T. Bazilevskiy

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16. Abstract

The origin and formation of various types of craters, both on the Earth and on other planetary bodies, are discussed. Various models are utilized to depict various potential causes of the types and forms of meteorite craters in our solar system, and the geologoical structures are also discussed.

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METEORITE CRATERS

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Craters — dish-shaped depressions with a circular wall surrounding them — are widely developed on the surface of the planets and satellites of the solar system. Nearly three centuries of astronomers have already observed craters on the Moon, and arguments about their origin have continued for nearly this entire time. Some consider the craters meteoritic, *i.e.*, occuring upon impacts of meteorites on the surface of the Moon, while others

*Numbers in the margin indicate pagination in the foreign text.

consider them volcanic, having appeared as a result of volcanic eruptions or collapses of the surface above destroyed magmatic reservoirs. However, these arguments went on chiefly inside a rather small group of specialists, having studied the Moon. For the majority of people, even for the majority of scientific naturalists, the craters of the Moon were only one of the curiosities of the lunar surface.

In our time, flights of space vessels to Mercury, Venus, Mars and its satellite, and the satellites of Jupiter and Saturn, have revealed an abundance of craters on these bodies which are very similar to lunar craters. It was roughly at this very same time that craters were discovered on the Earth, the majority of which were severely destroyed, and are probably "relatives" of the craters of the Moon. It became evident that the craters are formations which are typical for planets and satellites which have a hard surface, and, therefore, deserve the most intent study. With an increase in interest in craters, the arguments about their /24
origin became more severe. The question resounded as to whether meteorite craters existed at all.

Craters of the Moon and Other Heavenly Bodies

The history of the study of craters began with the craters of the Moon. We will begin our story with them[1]. The entire collection of lunar craters encompasses a hugh range of dimensions: from submicron microcraters on particles of the lunar soil to gigantic, multi-ring crater basins about 1,000 km in diameter. Besides craters, we do not know any other morphologically unique formations which encompass such a broad dimensional range. The lunar craters are customarily divided into three different categories: microcraters, small craters and large craters. The boundaries between them are rather conditional, and are primarily determined by the characteristics of observation and convenience of description.

Microcraters are dish-shaped depressions, usually with a

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[1]Bazilevskiy, A. T., Ivanov, B. A., Florenskiy, K. P. et al., Udarnye kratery na Lune i planetakh [Impact Craters on the Moon and Planets], Moscow, 1983.

wall surrounding them. The inner surface of a microcrater is often lined with a glass film, having formed during fusion of that mineral or rock on which the given crater is formed. Microcraters are located on the most diverse samples of lunar rock, which have in common the fact that, over a period of some time, they were located on the Moon's surface. According to the characteristics of their structure, lunar microcraters are similar to the microcrater formed in laboratories through the bombardment of different types of targets with high-speed micropellets. No one ever doubted that the lunar microcraters form with impacts on the lunar surface of micrometeorites, i.e., they are impact meteorite craters.

The small craters of the Moon, which are from several centimeters to 1-2 km in diameter, are also dish-shaped depressions, which are surrounded by a circular wall, which gradually changes into a zone of ejecta towards the periphery. In structure, they are similar to the craters, well-studied on the Earth, from the explosions of chemical or nuclear charges, and the formation of small craters because of explosive excavation and the dispersion of matter is indisputable. They are observed on all types of lunar surface: on basalt volcanic plains of the lunar "seas", on the ancient relief of the lunar continents, and the various elements of structure of newer and ancient large craters. And this indifference to the geological situation, combined with the "explosive" nature of their morphology, causes one to assume that small craters, just like microcraters, are a result of meteorite bombardment of the Moon's surface. The fact that the lunar rock are extremely poor in volatile substances, without which the broad development of volcanic eruptions is impossible, also favors this conclusion. What is more, in the lunar regolith, which represents ejecta of small craters superimposed one onto another, the admixture of meteoritic matter is identified by its geochemical characteristics, i.e., just as those "pellets" which, upon their collision with the Moon, formed both small craters and the lunar ground which is syngenetic with them — the regolith.

A definite diversity is observed in the structure of the small fresh craters of the Moon. Among the craters less than 50-100 m in diameter, simple dish-shaped forms predominate. Among the larger craters, three more typical morphological varieties are encountered: flat-bottomed, those with a central ridge, and concentric craters. The cause of the occurrence of various types of craters consists of the double-layer nature of the geological profile of the moon near the surface: the porous lunar regolith, several meters thick, lies on a rocky basalt or brecciated base[2].

The large craters of the Moon, more than 1-2 km in diameter, also reveal a regular change in their structure, as a function of size, which makes it possible to detect the various morphological types of large craters[3]. These craters, just like the small craters of the Moon, have a circular wall and a wide zone of ejecta surrounding them. Sometimes, in the very fresh craters, the peripheral parts of the ejecta form a characteristic picture of radially-divergent rays. The rays from the large craters are traced hundreds, and even thousands of kilometers, which assumes an initial /25 dispersion rate of the material on the order of 1 km/second.

On the whole, the morphology of large lunar craters unequivocally indicates their formation as a result of explosive excavation, and already is reminiscent of the depleted state of the rock on the Moon with respect to volatile components, forcing one to assume that these craters are not a result of volcanic eruptions, but are the traces of the impact of gigantic high-speed meteorites. This conclusion agrees with the fact that, in continental brecciae, formed by ejecta from large craters, just like in the regolith, an admixture of several percent of metorite matter is discernible.

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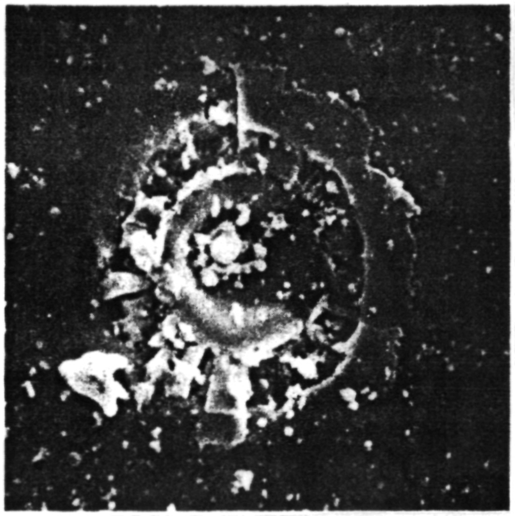
[2]Kvayd, U. L., Oberbek, V. L., "Opredelenie moshchnosti poverkhnostnogo sloya Luny" [Determination of the Thickness of the Moon's Surface Layer], in the collection: Mekhanika obrazovaniya voronok pri udare i vzryve [Mechanics of Formation of Craters During Impact and Explosion], Moscow, 1977, p. 86.

[3]Florenskiy, K. P., Bazilevskiy, A. T., Grebennik, A. A., "Morfologiya udarnykh kraterov na Lune i drugikh planetakh" [Morphology of Impact Craters on the Moon and Other Planets], in the collection: Meteoritnye struktury na poverkhnosti planet [Meteorite Structures on the Surface of Planets], Moscow, 1979, p. 192.

Presently, the conclusion on the impact origin of the large craters of the Moon is not disputed by hardly any of the geologists and planetologists. But comparatively recently, about 15-20 years ago, when the morphology of the lunar craters was already rather well-studied, but rock samples still had not been delivered to the Earth, many geologists, having studied these formations from photographs, showed a preference to the volcanic method of their formation, rather than the impact-meteoritic method. It was necessary to "import" rock samples from the Moon and ascertain that the volcanic phenomena on the Moon did not have an explosive nature, but represented vast and steady eruptions, and it was also necessary to obtain detailed images of other planets and satellites and detect craters on their surfaces, which were very similar to the lunar craters, prior to which the impact origin of the craters of the Moon had become a scientific fact which was not subject to doubt.

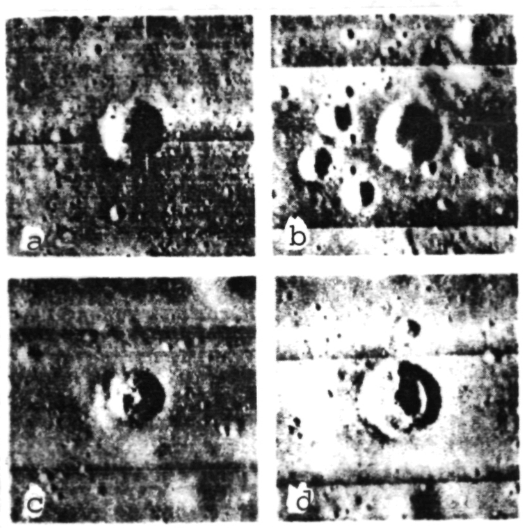
Craters on the reverse side of the Moon. Picture from the "Zond-8" space vehicle. Here, the largest crater — Aitken — has a diameter of about 170 km. The picture is quite typical for the Moon, the nature of the landscape of which is determined by the craters which are superimposed on one another.



Microcrater 30 microns in diameter on the surface of a particle of the lunar regolith. Photograph by O. D. Rode.

Granted, highly-specialized professionals abandoned these doubts, if they may be expressed thusly. Among geologists, far removed from planetology, distrust in the impact-meteoritic origin of the large craters of the Moon exists as before, which, among other things, prompted us to write this article.

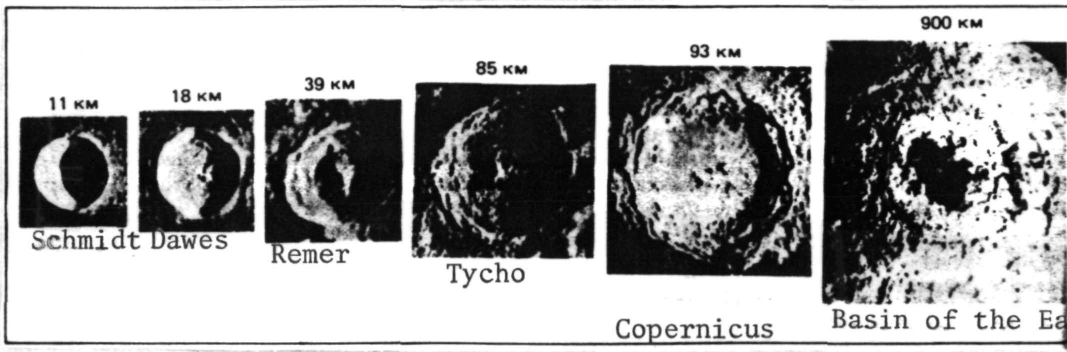
What then did we see on other planetary bodies? The craters of Mercury, Venus, Mars and its satellites, and the icy satellites of Jupiter and Saturn, are very similar to the craters of the Moon, although they have some differences, which are fully explainable by the specifics of these bodies. On the smallest bodies — Phobos and Deimos (the satellites of Mars) or Epimetheus (small icy satellite of Saturn) — simple dish-shaped craters are developed, and for rather large bodies, irrespective of the nature of their geological history and the composition of the surface, a shift in morphological types of craters from simple dish-shaped forms to craters with a central ridge, and even to circular basins, is characteristic. This generality of the morphology of the craters on bodies with different chemical and mineral compositions indicates the existence of some common cause of their formation, which /26
lies outside of these bodies, or is located inside of each of them. One may make a choice between the external and internal causes of the formation of these craters according to the data given below, since one can hardly speak seriously about explosive endogenous volcanism on the satellites of Mars with a diameter of 12 and 22 km, but the craters of the Earth help us to draw more substantiated conclusions.



Small craters on the surface of the lunar basalt plains. This is a fragment of a photograph from the "Lunar Orbiter-1" and "Lunar Orbiter-2" space vessels: a) dish-shpaed; b) flat-bottomed; c) with central ridge; d) concentric. Width of band on image is 180 m.

Craters of the Earth

In this section, we will not speak of the well-known volcanic craters and calderae, the origin of which is evident. Here, we will speak of the relatively small number (about 140 specimens) of structures, the impact-metoeoritic origin of which has been indisputably proved either by findings of meteoritic matter in them (craters of the Sikhote-Alin field, Kaaly and Henbury craters, Arizona meteorite crater), or by the detection of a number of signs of high-speed meteorite impact. Many of these structures had been related earlier to the category of cryptovolcanic (from the Greek χρυπτορ — secret, hidden), because of the vagueness of the connection of their structure with volcanism, and now, they are viewed as terrestrial analogs of the impact craters of the Moon and other heavenly bodies.



Various morphological types of large craters of the Moon. The name of the crater is given underneath, and its diameter above. The craters with a diameter of less than 15 km are dish-shaped (Schmidt). With an increase in the diameter, the bottom of the crater becomes flat, or even slightly convex (Dawes). With diameters of 25-40 km, nearly the entire bottom of the crater is occupied by a central ridge (Remer). For the interval of diameters from 30-200 km, craters with a nearly horizontal bottom are characteristic, in the center of which one (Tycho) or several (Copernicus) central ridges rise. On detailed photographs of these craters, it is evident that the surface of the bottom has a wrinkled nature, reminiscent of the surface of hardened lava. In craters with a diameter of more than 150 km, one or several circular elevations — the inner walls — appear on the bottom of the crater, instead of the central ridge. These craters have come to be called basins (Basin of the Eastern Sea).

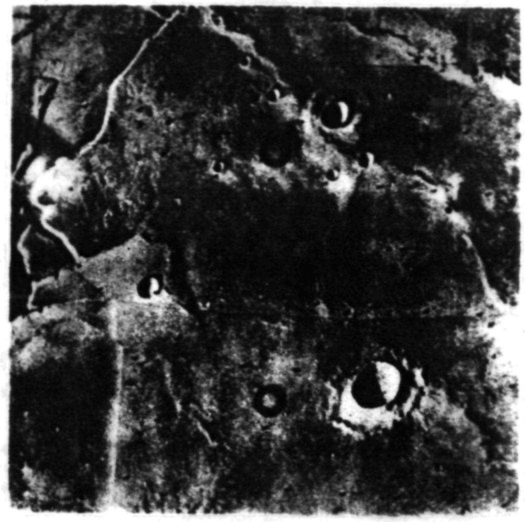
The Earth's meteoritic craters, or, as they are sometimes called, astroblemes, are represented by structures from several dozen meters to 100 km in diameter. Their age varies from 38 years (Sikhote-Alin craters) to 2 billion years (Vredefort in South

Africa). They are encountered in the most diverse geological situations, they are superposed on sedimentary, magmatic and metamorphic rock, and they obey only one single rule: they are relatively rare in geologically active regions, where they are quickly destroyed, and are more frequently encountered in stable ancient regions, for example on the Ukrainian, Baltic and Canadian plates, where the conditions for their preservation are far better. /27

In contrast to their analogs on other planets, the terrestrial craters are accessible for study by direct methods. In some craters which are laid bare by erosion, one may study the nature of their structure down deep and, which is very important, study the rock in various zones of the crater, comparing them with the very same rock which has not been affected by the processes of crater formation. In a number of cases, the structure of the craters was studied using drilling, since deposits of minerals are confined to some craters. For example, in the basin of the Boltyshskiy crater in the Ukraine, a gigantic stratum of oil shales formed, and some craters of the Northern American continent, buried under a layer of deposits, became collectors, in which commercial reserves of oil and gas accumulated.

The craters of the Earth, just like the craters of other planets and satellites, reveal the dependence of the nature of their structure on their dimensions. Craters less than 2 km in diameter in sedimentary rock, and less than 4 km in hard rock, have a simple, dish-shaped form, similar to the form of the dish-shaped craters of the Moon and other planetary bodies. Typical and well-studied examples of this type of craters are the Arizona crater in the USA, which is 1.2 km in diameter, and the Lonar crater in India, which is 1.8 km in diameter. In larger craters, a central ridge rises above the bottom, like, for example, in the Steinheim crater in the Federated Republic of Germany (D=3.5 km), and in the aforementioned Boltyshskiy crater in the Ukraine (D=22 km). Above the true bottom of the crater, the central ridges rise 0.1-2 km; however, because of the fact that the crater is filled with crushed displaced rock and other products of impact processing, the central

Continental region in the Northern Hemisphere of Mercury. The montage of photographs is from the "Mariner-10" space vehicle. The two largest craters in this region — Verdi (D=150 km) and Bakh (D=100 km) — are morphologically similar to the lunar craters Copernicus and Tycho. Among the smaller craters, there is a similarity to the lunar crater Remer, Dawes and Schmidt.



Craters on the Plain of Khris on Mars, close to the point of landing of the "Viking-1" space vehicle (montage of photographs from the orbital block of the vehicle). The largest craters here are similar to the lunar craters of the Dawes type, and the smallest craters are similar to the craters of the Schmidt type.

ridge either rises slightly above the visible bottom, or it is not visible at all. Therefore, the central ridges in the craters of other planetary bodies should also be considered the apexes of larger formations, which rise above the visible bottom of the crater. With a crater diameter of 23-60 km (as a function of the geological structure and composition of the target rock), circular unheavals form instead of the central ridge, and sometimes together with it. Examples of such craters are Ries in the Federated German Republic (D=23 km), and Manicouagan in Canada (D=70 km)[4]. Detected /28 in the rock of terrestrial meteoritic craters is the effect of powerful compression, having a pulsed or impact nature[5]. The

[4]Masaytis, V. L., Danilin, A. N., Mashchak, M. G., et al., Geologiya astroblem [Geology of Astroblemes], Leningrad, 1980; Val'ter, A. A., Ryabenko, V. A., Vzryvnye kratery Ukrainskogo shchita [Explosive Craters of the Ukrainian Plate], Kiev, 1977.

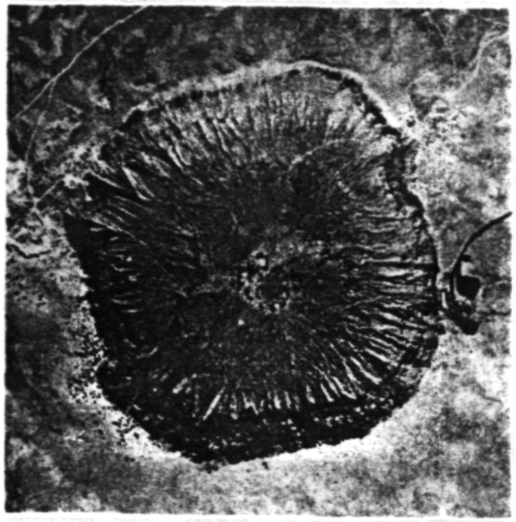
[5]Impaktity [Impactites], edited by A. A. Marakushev, Moscow, 1981.

huge volumes of rock of the target are re-crushed and transformed into a mixture of fragments — a breccia. The quartz in them is partially transformed into high-pressure minerals — coesite and stishovite — and graphite changes into hexagonal and cubic modifications of diamonds. In this case, the structure of the minerals

Impact craters of Venus. Montage of radar images from the "Venera-15" and "Venera-16" space vehicles. Lower lert — ancient two-ring impact basin about 100 km in diameter, upper right — crater about 60 km in diameter with a central ridge and an asymmetric zone of ejecta.

Craters on the icy surface of the Ganymede satellite of Jupiter. The picture is from the "Voyager-2" space vehicle. The small craters are dish-shaped. Central ridges are characteristic for the large craters.

is distorted, sometimes right up to its total disordering and transition of the matter to a vitreous state. Thus, without fusion, and only because of the highly-porous mechanical deformations, diaplectic glass occur. In the very same case, when very large impact loads are in effect, the matter fuses, and, as a result, we see strata of solidified impact fusion in terrestrial meteoritic craters, mixed with fragments of unfused rock, and often containing an admixture of meteoritic matter, usually identified by the increased content of such elements as iridium, and sometimes nickel.



Arizona meteorite crater on Earth, with a diameter of 1.2 km. Found in the crater and around it is a large number of fragments of an iron meteorite, called "Devil's Canyon", The crater was formed roughly 50 thousand years ago.

(D=50 km), is comparable to the volume of the crater itself. This creates an unsolvable problem, in our opinion: where to place this hypothetical explosive fluid and how to protect it from premature leakage to the surface.

The hypothesis of "impact from below" becomes even more vulnerable if one turns to craters on other planets and satellites, where the composition of the rock of the target varies from basalts and other basic rock or matter of the chondrite type to H_2O ice, the temperature varies from +500 to -200° C, and the diameters of the bodies on which the craters are detected vary from 10 to 1200 km, without disruption of the above-described morphological sequence and the nature of distribution of the structures as a function of size. The nature and intensity of the geological processes on these planetary bodies depends very strongly on the dimensions of the body and its total chemical composition[7]. The very nature of the craters is surprisingly uniform.

Under these conditions, meteorite (and possibly comet) impacts should be recognized as the most natural cause of the formation of craters, which is corroborated by the fact that, in the rock of these craters, it is actually often possible to identify an admixture of meteroite matter. What is more, astronomic observations of asteroids and comets show that the orbits of some of them intersect with the orbits of the Earth and other planetary bodies and, consequently, such collisions are unavoidable in the geological time scale.

Thus, we are forced to conclude that meteorite craters actually

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[7]Barsukov, V. L., Bazilevskiy, A. T., "Sravnitel'naya planetologiya. Nekotorye itogi i perspektivy" [Comparative Planetology. Some Results and Perspectives], in the collection: Reports of the 27th International Geological Congress, Vol. 19, Moscow, 1984, p. 3.

exist and, what is more, are widely disseminated on the solid bodies of the Solar System.

Physics and Mechanics of Meteoritic Impact

In order to understand what one may find at the point of impact of a meteorite, we will try to represent a high-speed meteorite impact as a sequence of interrelated events.

Upon approaching a planetary body, a meteorite of sufficiently large dimensions and sufficiently low strength may be destroyed by the tidal forces into several fragments, which move along similar trajectories. If the dimensions of the fragments are sufficient for breaking through the atmosphere, their descent may create structures of the same age which are next to one another. Most well known are /30 the numerous cases of paired descents, although there are evidences of the simultaneous descent of many bodies.

The rates of approach of modern meteorite bodies to the Earth lie in the range from 11.2 to 70 km/sec. The entry of compact bodies into the atmosphere at these rates creates collossal aerodynamic and thermal loads on the body. There occurs ablation of the material from the surface of the body, and, possibly, its total destruction.

By external manifestations, the passage through the atmosphere of a high-speed body is similar to the detonation of a linear charge of an explosive substance (for example, a detonation fuse), located along the trajectory of descent. A ballistic wave, descending to the surface of the ground and reflecting from it, may also create considerable impact and wind loads. It is precisely such a ballistic wave which created the characteristic inrush of the forest at the epicenter of the Tungusskiy occurrence of 1908[8]. With high speeds of the body, light and thermal radiation of the air shock wave plays a substantial role in the picture of flow-around of the body[9].

[8]Tsikulin, M. A., Udarnye volny pri dvizhenii v atmosfere krupnykh meteoritnykh tel [Shock Waves With the Movement of Large Meteorite Bodies in the Atmosphere], Moscow, 1969.

[9]Nemchinov, I. V., Tsikulin, M. A., Geomagnetizm i aeronomiya 3/4, 636 (1963); Nemchinov, I. V., Orlova, T. I., Svettsov, V. V., Doklady AN SSSR 231/5, 1084 (1976).

The intensity of the ballistic shock wave depends on the parameters of the atmosphere. Therefore, for example, in the atmosphere of Venus, the shock waves from meteorites have considerably higher parameters than in the Earth's atmosphere.

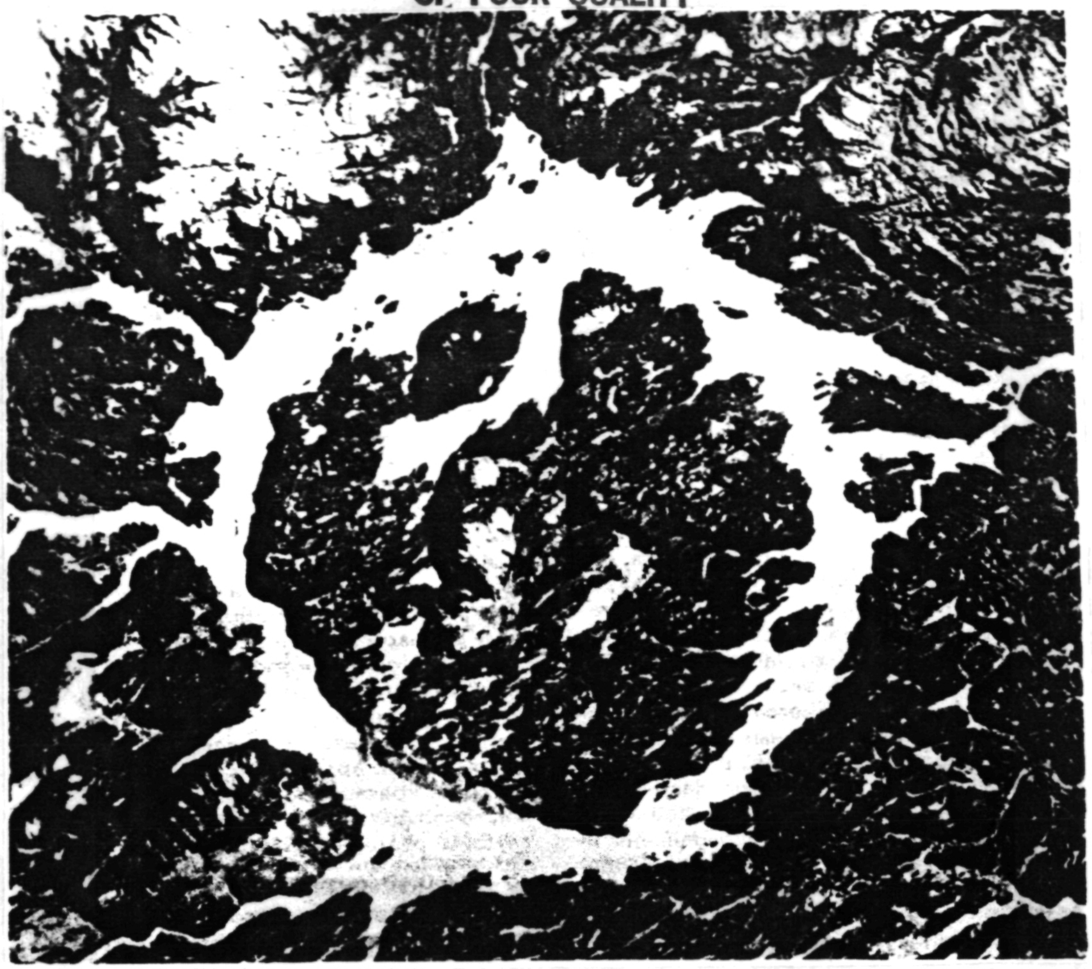
The largest of the meteorite structures, observed on the planets and satellites, were formed by the descent of bodies over 10 km in diameter. The descent of such bodies to the planets with an atmosphere should have been accompanied by its "pulverization". Thus, global oscillations of the atmosphere, similar, for example, to those which were recorded during the eruption of the Krakatoa volcano and the descent of the Tungusskiy meteorite, should have accompanied the formation of "holes" in the atmosphere and its subsequent inflow.

But here the meteorite, having overcome the atmosphere, cuts into the solid mantle of the planetary body. Its sharp braking begins, accompanied by a nearly instantaneous conversion of its kinetic energy into the kinetic and thermal energy of the matter of the planet's crust. At the point of impact, a powerful shock wave is generated, which propagates into the depths of the planet. Behind the front of the shock wave, the matter is in a state of dynamic compression — compression by motion. In proportion to the arrival of discharge waves from the surface, the pressure at each point gradually decreases from the peak value at the front of the wave to the corresponding residual value. Abrupt compression of the matter of the rock, accompanied by an irreversible increase in entropy, takes place at the very front of the shock wave. As a result, the unloaded matter remains heated to a temperature which exceeds the initial temperature.

As a function of the pressure on the shock front, the magnitude of this temperature changes, with a possible change in the aggregate state of the matter as well. Even with a rate of impact of 4 km/sec, a pressure of 0.5 megabars is achieved in dense igneous rock, and the first batches of impact fusion appear. With a rate of impact of over 7-8 km/sec, the maximum pressures reach 1 megabar. With unloading from such pressures, the matter turns out to be partially vaporized. From these evaluations, it is evident that on the Earth, with average rates of descent (15-20 km/sec), a meteorite impact is sure to be accompanied by processes of fusion and vaporization of the rock. Only the composition of the rock at the point of impact introduces corrections to this assertion. Thus, with impact compression, limestones undergo thermal dissociation, giving products which are different from the impact fusion in the igneous rock.

Propagating to the sides and into the depths of the planet, the shock wave encompasses ever greater masses of matter, and the peak pressures at its front decrease. The consequences of impact compression for the matter also change. With pressures on the wave front of 150-300 kilobars and higher, nearly all of the basic rock-forming minerals undergo polymorphous phase transitions, with an increase in density. With unloading, the basic amount of the matter returns from the high-pressure phase to the initial state of the low-pressure phase. But a small part of the matter may prove to be under conditions of hardening, both on the microlevel (within the limits of cracks and planar elements of some kind of mineral granule) and on the macrolevel (for example, with the introduction of impact fusion into the cracks in the bottom of a growing crater). In this case, minerals which are thermodynamically stably existing /31 at depths of tens of kilometers (stishovite, coesite, diamond, and others) may be detected in rock samples from the crater, lying on the diurnal surface.

With pressures on the wave front below 100 kilobars, primarily mechanical transformations occur in the rock: destruction, crushing, crack formation. But the volume of the matter, having undergone such transformations, exceeds the volume of the zone of fusion and vaporization by 10-100 times. The most appreciable result of the mechanical destruction of the rock under the crater is the negative anomaly of the force of gravity, the existence of which is associated with the dispersion of the destroyed rock. In some cases, a characteristic striated texture of the surface, referred to as impact cones or shock cones, is observed on samples from the



Ancient impact crater on the Earth — Manicouagan — with a diameter of about 70 km. The photograph is from the "Landsat" space vehicle. The crater has a two-ring structure. The picture was taken in winter, when the snow, having accumulated in the circular trough between the remnants of the outer and inner circular wall, emphasizes the circular form of the structure.

zone of destruction.

Finally, after passage of the shock wave, the matter does not remain at the initial point, but, by virtue of the dynamic nature of the impact compression, spreads and scatters at considerable rates, which uniformly decrease in proportion to the distance from the point of impact.

Proceeding from this picture of meteoritic impact, it is necessary to recognize that, at the point of high-speed impact, we should find (and will find!) mechanically crushed displaced and undisplaced

rock (called allogenic and authigenic breccia, respectively) and /32
hardened fusion of approximately the same chemical composition as the surrounding rock, mixed, to some degree or another, with unfused fragments (so-called tagamites and suevites). What is more, it is sometimes possible to identify traces of condensate, having precipitated from a cloud of impact vapor on colder rock fragments. The rock fragments from the zone of polymorphous transitions carry traces of reversible and irreversible changes in their minerals, having accompanied the front of a shock wave. It is characteristic that, in well-preserved structures, all of the material evidence of transformation of the matter upon meteorite impact, listed above, are detected in proportions expected namely for a high-speed meteorite impact.

Thus, from the point of view of physics and mechanics, practically everything that should have occurred on the planet surface, as a result of a high-speed-impact, was found. The unanswered questions, associated with the transformation of matter, bear a "local" nature, and are successfully answered in proportion to the development of calculation and experimental methods. And even more remains to be understood in the processes of fusion and volatilization of rock — formations of polymineral composition. For example, the details of polymorphous phase transitions or the very causes of the conservation and non-conservation of high-pressure phases during unloading are unclear. The list of such problems is large, but they all may be solved on the already-created basis of accumulated fact, verified models and ascertained limitations.

We have consciously not touched upon questions associated with the most easily observed characteristics of craters — their form — to this point in time. And here is one of the very interesting, and still not understood, problems of the reaction of the crust of any planetary body to the formation of a meteorite crater.

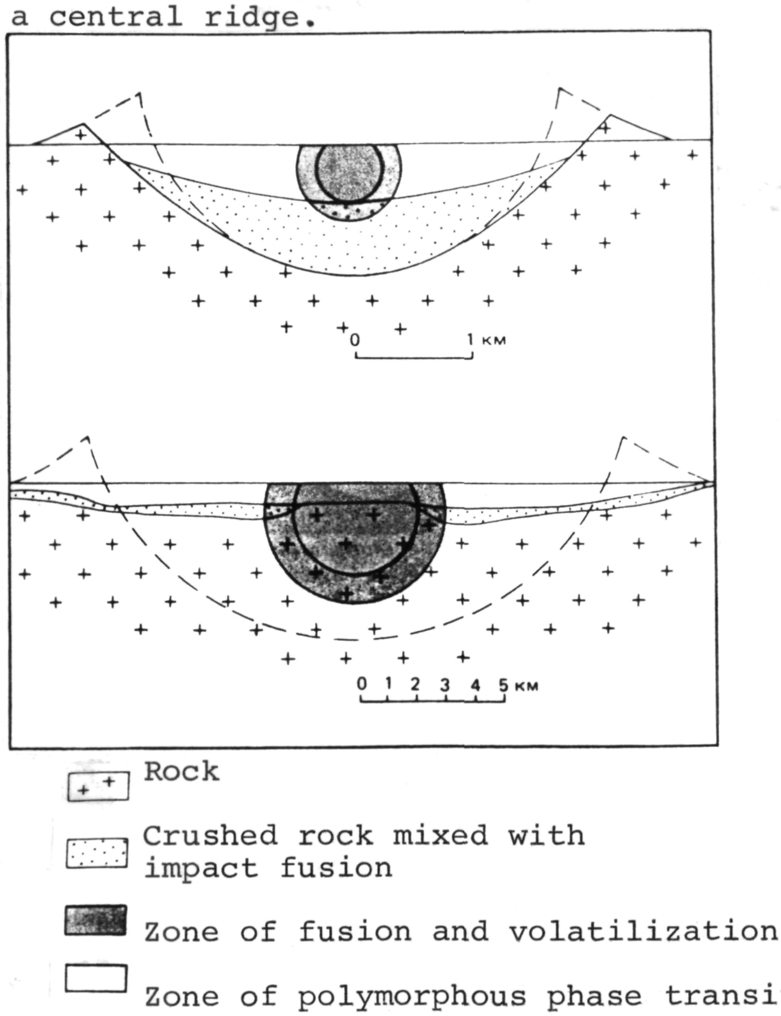
Why are Large Craters so Flat?

As we have already said, large craters of various planetary bodies form a common morphological series, in which the dish-shaped craters alternate with craters with a central ridge, and those — with multi-ring basins. In this case, not only the form of the crater changes, but also such of its parameters as the relationship of the depth or height to its diameter. According to the known reasons, the visible parameters of the crater are most often measured on other planets. On the Eath, we have the possibillity of determining the true depth, along with the visible depth.

The dish-shaped craters of all planetary bodies are similar to one another, not only in external appearance, but also with regard to diameter and visible depth: the depth from the apex of the wall to the bottom is an average of 1/5 the diameter of the crater at the crest of the wall. On the Earth, the majority of the craters, because of erosion, are lacking a filled wall, which explains their lesser depth. However, in the best-preserved examples, the relationship of the visible depth to the diameter is close to the "general-planet" ratio (for example, in the Arizona crater, it is 1:5.3). Roughly the very same relationship of the visible depth and the diameter is characteristic for the experimentally-obtained explosion craters on a scale of 10 cm-10 m, which indicates the great similarity between impact formation of a crater and an explosion near the surface.

With a shift in morphological type, which takes place in that case when the crater reaches some critical diameter, the dependence of the visible depth of the crater on its diameter also changes. For complex craters with a central ridge and multi-ring basins, the maximum depth increases roughly propotionally to the cube root of D. As a result, the visible depth of terrestrial craters does not exceed 0.5 km, while the depth of craters on other planetary bodies is a total of 3-4 km, with diameters in the hundreds of kilometers. Analysis of the craters on Earth indicates that the true depth of the craters also obeys a similar dependence. Thus, with a shift in the morphological type, the relationship between the maximum height of the crater wall and the diameter of the crater changes: for dish-shaped craters, the wall height increases in proportion to the depth, and for more complex craters — much more slowly.

The set of data, obtained for various planets and satellites, makes it possible to draw the first conclusion relative to the reasons which affect the morphology of large craters: the critical diameter, above which complex, relatively shallow craters may exist, which is inversely proportional to the force of gravity on the surface of the planetary body. Against the background of this main dependence, variations, associated with the characteristics of the geological section of the given locale, are observed in the magnitude of the critical diameters of the craters. For example, on Mars, one may find craters in various regions with a diameter /33 from 5 to 10 km, both dish-shaped in form and flat-bottomed with a central ridge.



Profiles of "true" and visible craters of various sizes (solid line), as compared to hypothetical transition craters (dotted line) and the contours of the initial position of the zones of fusion and volatilization and the zones of polymorphous phase transitions. With an increase in the scale of the crater, the effect of the force of gravity decreases the relative dimensions of the crater and increases the relative dimensions of the zones of fusion, volatilization and phase transformations. From top to bottom, the given craters are: Brent (Canada) and Boltyshskiy (USSR).

The small relative depth of complex craters, as indicated by analysis of the available data, is primarily a result of the irreversible transformation of the original deep transition craters, which occur upon meteorite impact. A similar transformation not only catastrophically reduces the depth of the craters, but also leads to raising of the strata of rock under the bottom of the crater above the level of their initial placement. The mechanics of this process have not yet been quantitatively developed, and we still may only cite some data, which describe the scale of the process of planation of the crater.

The numerous calculations of a high-speed impact show that, in the case when the density of the projectile is comparable to the density of the rock of the target, the formation of a rather deep dish-shaped depression upon braking of the projectile is unavoidable. The scaling of these results to the case of formation of craters 50-100 km in diameter leads to the estimation of the depth of the transition crater as 10-20 km. These very same values of the depth of the transition crater are arrived at through attempts to compare the changes, observed in the minerals of rock from wells drilled in the center of several craters, with the results of two-dimensional numerical calculations of high-speed impacts. Yet another result of these very same calculations is the expected hemispherical initial form of the volume of the rock which is subjected to impact fusion.

The direct geological data on craters in stratified targets, obtained by means of drilling and geophysical studies, irrefutably indicate raising of the layers below the central ridge by roughly 1/10 the radius of the crater[10].

What is more, careful measurements of the profiles of lunar craters show that, in craters over 50 km in diameter, the apex of the central ridge is located at the level of the initial surface, and sometimes even 0.5-1 km above it. Taking into account the fact that the dimensions of the projectiles, which form such craters, are several kilometers, we irrefutably arrive at the /34

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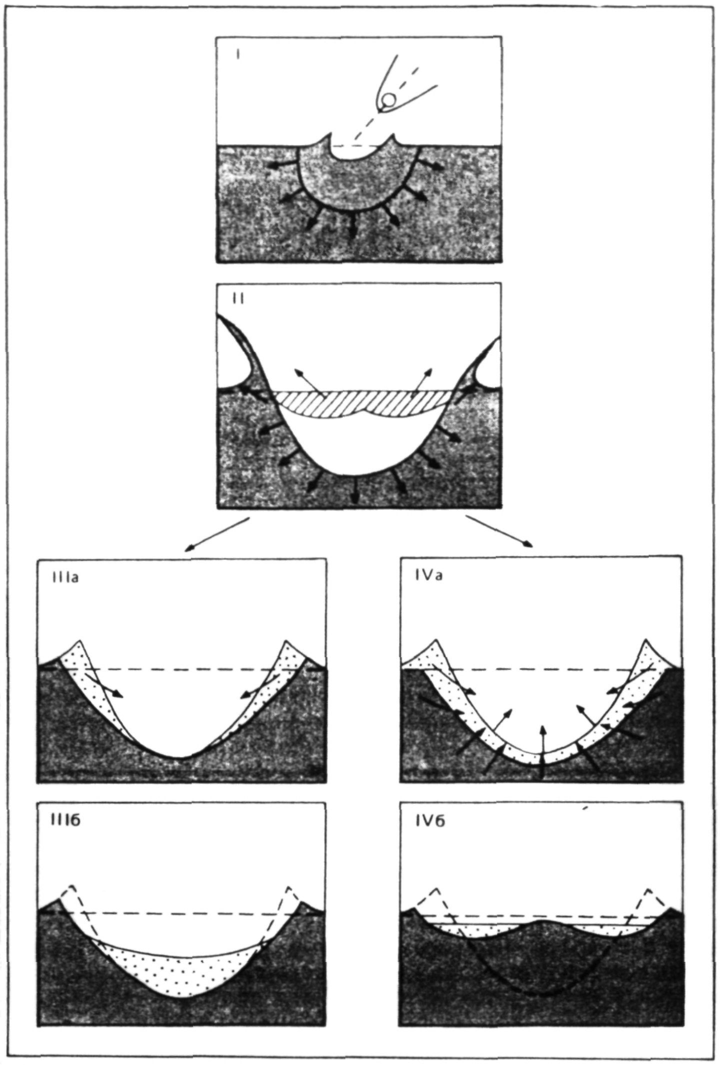
[10] Ivanov, B. A., Bazilevskiy, A. T., Sazonova, L. B., "Ob obrazovanii tsentral'nogo podnyatiya v meteoritnykh kraterakh" [Formation of the Central Unheaval in Meteorite Craters], Meteoritika, 40, Moscow, 1982, p. 67.



Rock

Rock compressed by shock wave

Rock ejected as a result of impact

Crushed rock mixed with impact fusion

Direction of movement of material

Approximate scenarioes of the formation of meteorite craters.

I. Havings approached the surface of a planet, the meteorite strikes it, and a shock wave propagates from the point of impact, which sets the matter in motion — the cavity of the future crater begins to grow.
II. Partially because of the blow-out, and partially because of the transformation and extrusion of the destroyed rock, the cavity reaches its maximum depth — a temporary transition crater forms.
III. With a small scale of the impact, the transition crater may prove to be stable, and become simply a crater from the transition crater (IIIa); in other cases, the destroyed material slides from the sides of the crater, and the bowl of the "true" crater fills with it (IIIb).
IV. In an impact event of larger scale, the processes of loss of stability, which are still unclear, lead to rapid upheaval of the bottom of the crater, accompanied by collapsing and subsidence of the peripheral parts of the crater — thus a crater with a central ridge occurs (IVa); in this case, the circular depression of the crater is filled with a mixture of fragments and impact fusion (IVb).

conclusion of the existence of a phase of inverse motion of the bottom of the crater in the direction of the surface. It remains to answer the question of the amplitude of this movement and of its mechanism.

Geological data make it possible to also make some evaluations of the rate of this unheaval. It is firmly established that the impact fusion in terrestrial meteorite craters is always located in the form of subhorizontal deposits around a central unheaval. This indicates that it lost its viscosity even after the formation of the observed true bottom of the crater. In this case, it is common knowledge that the rapid cooling of the fusions because of mixing with a large number of cold fragments of rock, accompanied by a sharp increase in viscosity, is a characteristic feature of impact fusions. For typical conditions of formation of craters, the cooling time of the fusion to a temperature in equilibrium with the fragments, when the fusion is already hardening, is about 100 sec[11]. Further cooling of the deposits of hardened fusion may last thousands of years, because of thermal conductivity. /35

Based on these and other data, one may paint an approximate scenario of the formation of meteorite craters of different sizes. After impact of the meteorite and passage of the shock wave, the rock of the target moves along complex trajectories, which leads to an increase in the dish-shaped transition cavity, with regard to the depth to diameter, by roughly 1/3. The rock in the upper part of the cavity is ejected at some angle to the horizon, and is deposited around the crater. The lower part of the cavity is formed because of the forcing out of rock downward and to the sides, which leads, on the one hand, to the elevation of the surface of the ground around the cavity and, on the other hand, to the extrusion of part of the volume of the cavity to "infinity" in the form of a compressional wave. This process may be considered, in the first approximation, to be adequate for events of any scale. The further course of events is principally different, and is determined primarily by the scale of the event. In a small scale,

[11]Onorato, P. et al., J. Geophys. Res. 83/135, 2789 (1978).

the bottom of the transition cavity proves to be stable, and does not change its form and position in space. The wall of the transition cavity, made up of crushed material, loses stability and caves in, partially filling the crater[12]. In events of a large scale, the bottom of the transition cavity proves to be unstable, and the cavity rapidly regenerates, so that it is as if the rock under the crater had been first elastically deformed. As a result of such "elastic recoil", as a function of the scale and characteristics of the geological structure, either a central unheaval or a system of concentric rings may occur. One may also assume that the surface around the transition cavity collapses during its "elastic" regeneration, increasing the visible diameter of the crater depression.

Unfortunately, this scenario has only partially been quantitatively calculated. The total mechanical model of the reaction of the hard crust of planetary bodies to a meteorite impact of large scale has not yet been created[13].

Thus, meteorite craters exist. They are not something exotic, but they occupy a rather considerable place in the series of natural events, which take place in our solar system. The craters determine the landscape of many planetary bodies. On other bodies, they are relatively rare, only because of the constant regeneration of the surface by geological processes.

We are compelled to still take into account, along with the fact of the existence of meteorite craters, what their cause is. The Earth is not very reliably shielded by its thin atmosphere from external effects, including the impacts of meteorites. In 1908, the relatively small Tungusskiy meteorite (or center of a

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[12]Grieve, R. A. F., Garvin, J. B., J. Geophys. Res. 89/B13, 11,561 (1984).

[13]A survey of available mechanical models of this process has been made by B. A. Ivanov, entitled: Mekhanika krateroobrazovaniya [Mechanics of Crater Formation], in the series Itogi nauki. Mekhanika tverdogo deformiruemogo tela [Results of Science. Mechanics of a Deformable Solid Body], Vol. 14, VINITI Publishers, Moscow, 1981, p. 60.

comet), with a "total" energy of 10-20 megatons of dynamite, generated an effect felt for thousand of kilometers. In 1947, the Sikhote-Alin meteorite shattered above the taiga, and created a vast crater field. And, although the probability of the impact of a sufficiently large meteorite in a populated area is extremely small, a simple impact of a kilometric asteroid on a continent or in the ocean (which is equivalent to the explosion of 300 thousand atomic bombs, having destroyed Hiroshima!) would cause long-term global changes in the climate of the Earth. Therefore, the realization of the reality of meteorite craters is still necessary in order to understand how vulnerable life on Earth is. Perhaps it is already time to pose the question of the creation of a permanent space patrol to prevent a possible meteorite impact, although it is very unlikely.

We would like to draw one more "purely geological" conclusion in closing. If models of large-scale unheavals of rock under terrestrial meteorite craters, up to 10-20 km in amplitude, were corroborated, then, evidently, it would make sense to analyze the possibility of superdeep drilling in the central unheavals of large meteorite craters, where, because of a cosmic event, the interior of the Earth became very slightly nearer.

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